A Percolative Model of Soft Breakdown in Ultrathin Oxides

[1]C. Pennetta, [1]L. Reggiani and [2]Gy. Trefán

[1]INFM - National Nanotechnology Laboratory, Dipartimento di Ingegneria dell'Innovazione
Università di Lecce, Via Arnesano, I-73100, Italy
[2]Eindhoven University of Technology, Dept. of Electrical Engineering
5600 MB Eindhoven, The Netherlands

Abstract

The degradation of ultrathin oxide layers in the presence of a stress voltage is modeled in terms of two antagonist percolation processes taking place in a random resistor network. The resistance and leakage current fluctuations are studied by Monte Carlo simulations for voltages below the breakdown threshold. An increase of excess noise together with a noticeable non-Gaussian behavior is found in the pre-breakdown regime in agreement with experimental results.

Keywords: breakdown, dielectrics, Monte Carlo, percolation

1. Introduction and model

Soft breakdown occurs in ultrathin oxide layers during constant voltage stress. This process manifests itself by a large increase of the stress-induced leakage currents (SILC) and by the occurrence of giant current fluctuations associated with resistance fluctuations. These fluctuations can be related to trapping and detrapping of electrons in the percolation cluster formed between the electrodes of the capacitor at the soft breakdown [1,2]. In this paper, we investigate the resistance in the pre-breakdown region and the associated fluctuations using two percolations which evolve in competition on a random resistor network [3], as briefly summarized below. We describe a thin film as a two-dimensional square-lattice network of resistors of resistance r_n, laying on an insulating substrate at temperature T_0 acting as a thermal reservoir. Geometrical effects arising from different shapes are neglected. Initially all the resistors are identical, $r_n = r_0$. We take a square geometry $N \times N$ where N determines the linear sizes of the lattice and $N_{tot} = 2N^2$ is the total number of resistors. Electrical contacts, realized by perfectly conducting bars, are placed at the left and right hand sides of the network where a constant voltage V is applied. By increasing the applied voltage, defects are introduced by replacing single resistors with short circuits. Thus, the network degrades by undergoing an insulator-conductor transition when the defects gradually become so dense that finally they form a continuous short circuit path between the contacts [3]. The temperature T_n of the n-th resistor is computed by [3]:

$$T_n = T_0 + A\Big[r_n i_n^2 + \frac{B}{N_{neig}} \sum_{l=1}^{N_{neig}} \Big(r_l i_l^2 - r_n i_n^2\Big)\Big] \tag{1}$$

where the term which adds to T_0 in the r.h.s. of Eq. (1) accounts for Joule heating associated with the current flowing in the resistor and the coupling with the nearest neighbours. Here, N_{neig} is the number of first neighbours around the n-th resistor with current i_n, A the heat coupling parameter and $B = 3/4$ provides a uniform heating everywhere in the perfect network. We note that Eq. (1) assumes an instantaneous thermalisation between neighbor resistors. Probabilities of creating and recovering a defect are taken as $W_D = exp(-E_D/K_B T_n)$ and $W_R = exp(-E_R/K_B T_n)$ with E_D and E_R characteristic activation energies, respectively, and K_B the Boltzmann constant. Monte Carlo simulations are carried out using the following procedure. (i) Starting from the perfect lattice, we calculate the total network resistance R, the external current I, and the local currents by solving Kirchhoff's loop equations by the Gauss elimination method. The local temperatures are then calculated and used for the successive update of the network. (ii) The defects are generated with probability W_D. The local currents and the local temperatures are then

recalculated. (iii) The defects are recovered with probability W_R, and the total network resistance, the local currents, and the temperatures are finally calculated. This procedure is iterated from (ii). Each iteration step can be associated with an elementary time step. The iteration runs until either the defect percolation threshold is reached (i.e. the network resistance drops below 10^{-3} times to its initial value), or steady-state is achieved. In this latter case, the iteration is let to run long enough for a fluctuation analysis to be carried out.

2. Results and discussion

We compare the results of numerical simulations to the corresponding experimental observations and validate the present approach by showing that it reproduces the key experimental features. Since soft breakdown experiments report leakage current evolutions, noise spectra and probability density of fluctuations, we investigate the same quantities by numerical simulations. In the simulations we applied a constant voltage stress with the following realistic parameters $N = 75$, $r_0 = 10^7\ \Omega$, $T_0 = 300\ K$, $A = 5 \times 10^7\ {}^oC/W$, $E_D = 0.19\ eV$, $E_R = 0.13\ eV$. Figure 1 reports the leakage current evolutions for stress voltages, respectively, of 0.1, 0.3, 0.5, 0.6, 0.7, 0.8, 0.85 and 0.9 V. We note that the values of the activation energies E_D and E_R control the speed of the evolution toward steady state and/or breakdown and as such should be calibrated from a quantitative comparison with experiments. However, the qualitative features of the breakdown process we are presently interested in do not depend significantly from their absolute values. We found that for voltages lower than 0.9 V no breakdown occurs but a dynamical balance takes place between defect generation and defect recovery. The steady state so achieved exhibits current fluctuations whose statistical and spectral features characterize the electrical quality of the dielectric. However, for stress voltages equal or larger than 0.9 V after a few thousand iteration steps the leakage current grows more than a thousand fold which indicates a breakdown situation. We also observe that the breakdown does not occur as a result of a systematic current growth but more as a result of current bursts. In fact, a set of bursts generally occurs that lead to the breakdown of the insulator. Thus an interesting pre-breakdown region appears like in experiments [4,5]. From a detailed analysis of a set of simulations we also conclude that a threshold voltage exists below which no breakdown occurs. Figure 2 shows how the breakdown voltage depends on the resistance of the virgin dielectric, modeled as an initial perfect lattice with increasing value of the elemental resistor. This breakdown voltage is found to increase proportional to the square root of the perfect network resistance. Figure 3 shows the steady state current noise spec-

trum calculated by FFT for stress voltages ranging from 0.1 to 0.85 V. Within numerical uncertainity, we detect Lorentzian spectra of the same corner frequency which indicates that the characteristic times of fluctuations are independent of stress voltages. Interestingly, the strong increase of the value of the plateaux at increasing stress voltages shows a super-quadratic increase of the noise with the applied stress. The current-noise spectra in Fig. 3 are found to be in qualitative agreement with experiments [4]. Figure 4 reports the normalized variance of resistance fluctuations as a function of the applied voltage. Starting from the intrinsic value of the network [6], the variance is found to increase significantly as a net effect of the stressing voltage which is ultimately responsible of the breakdown at about 0.9 V. Recent observations of SILC measurements reported non-Gaussian current fluctuations in the soft breakdown region of ultra-thin dielectrics [1]. Therefore, we computed the distribution function of the current fluctuations $P(I)$ for stress voltages of 0.5 V and 0.85 V and plotted them in Fig. 5 as a function of $I - < I >$, where $< I >$ is the average current value. On this linear-log plot the corresponding Gaussian distribution would be a downward parabola. The distribution for an applied voltage near breakdown of 0.85 V clearly exhibits a non-Gaussian tail at high currents over the average due to the large upward bursts which are not balanced by downward bursts in the current evolution. Since a further increase of the stress voltage causes the film to break down, the emerging non-Gaussian distribution can be thought of as a precursor of failure as observed in experiments [1].

3. Conclusions

We have developed a percolative approach to study the soft breakdown and the associated current fluctuations of ultrathin insulating films.The major results we found are summarized as follows. (i) The current evolution exhibits a pre-breakdown region. (ii) A threshold voltage depending on the resistance of the otherwise perfect film separates breakdown and steady state conditions. (iii) The spectrum of the current fluctuations is basically of Lorentzian type with a correlation time which is practically independent of the stress voltage. (iv) The variance of resistance fluctuations exhibits a giant super-quadratic enhancement at increasing the stress voltage. (v) At high enough voltage stress the current fluctuations exhibit a non-Gaussian behavior. These features, particularly the super-quadratic and the non-Gaussian behaviors of the current noise at high stress, are of relevant interest as failure precursors. These results are in satisfactory qualitative agreement with experimental findings.

Acknowledgements

This research is performed within the STATE project of INFM. Partial support is also provided by CNR MADESS II project.

References

[1] N. Vandewalle et al., Appl. Phys. Lett. 74 (1999) 1579.
[2] M. Houssa et al., Appl. Phys. Lett. 73 (1998) 514.
[3] C. Pennetta et al., IEEE Trans. on Electron. Dev. 47 (2000) 1986.
[4] G. Alers et al., Appl. Phys. Lett. 69 (1996) 2885.
[5] D.J. DiMaria and J.H. Stathis, Appl. Phys. Lett. 70 (1997) 2708
[6] C. Pennetta et al., Phys. Rev. Lett. 85, (2000) 5238.

Figure Captions

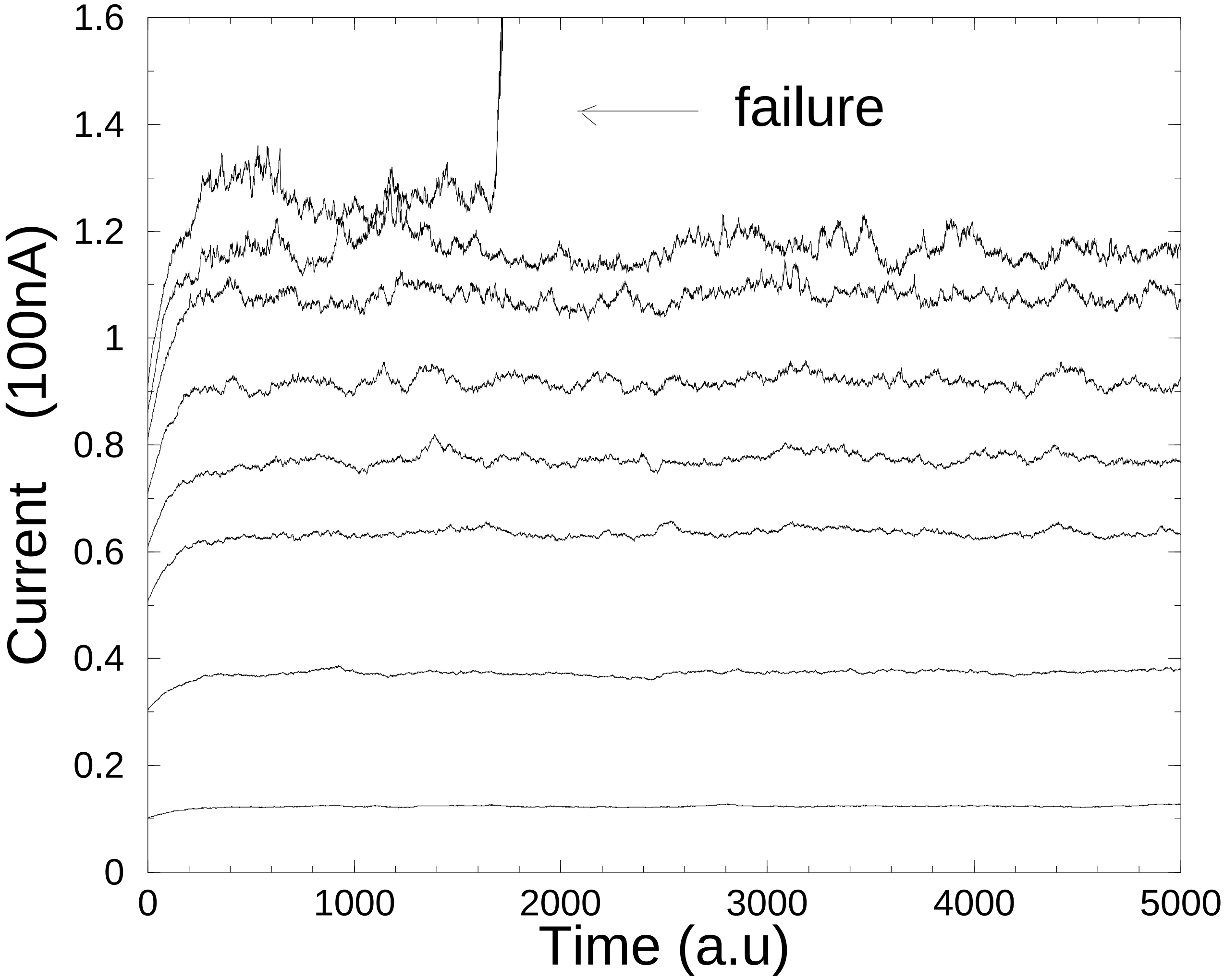
Figure 1 - Leakage current evolutions in a degrading dielectric kept under constant voltage for stress voltages (from bottom to top) of: 0.1, 0.3, 0.5, 0.6, 0.7, 0.8, 0.85 and 0.9 V.

Figure 2 - Breakdown voltage V_b as a function of the perfect network resistance R_{per}. The graph shows $V_b \propto \sqrt{R_{per}}$.

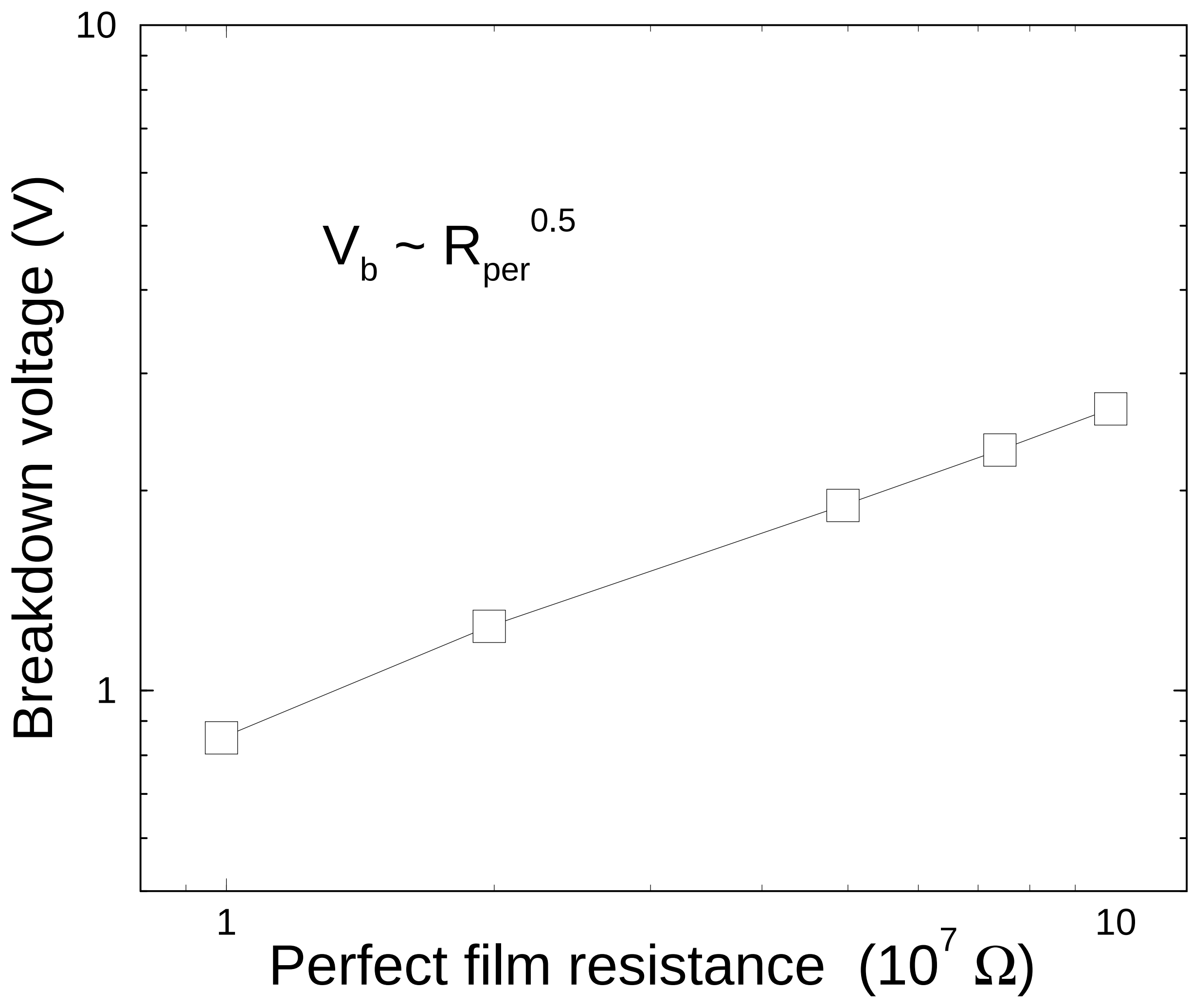
Figure 3 - Power spectral density of current fluctuations of the steady-state dielectric film kept under constant voltage of (from bottom to top): 0.1, 0.3, 0.5, 0.6, 0.7 and 0.85 V.

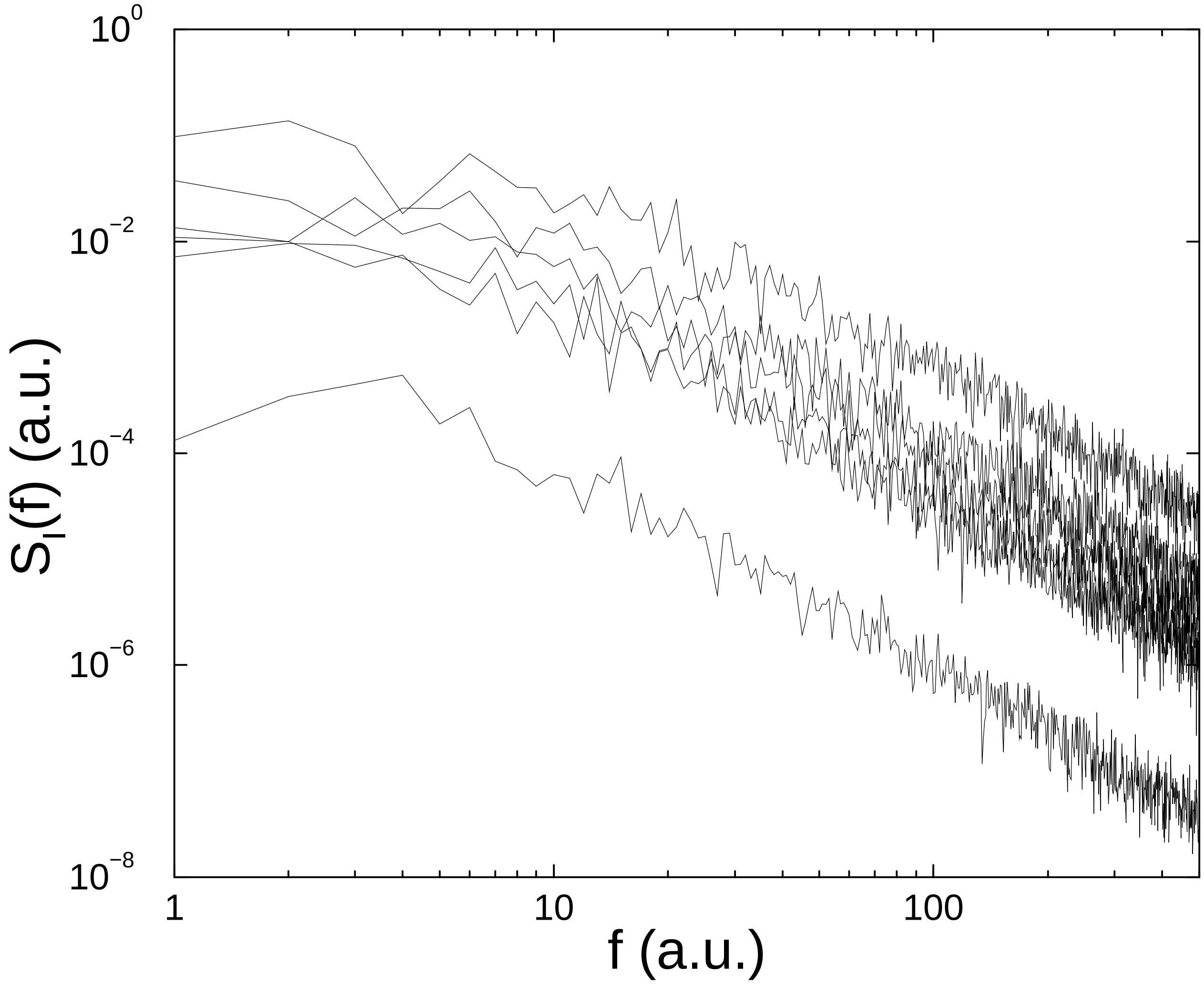
Figure 4 - Normalized variance of the network resistance fluctuations as a function of the applied voltage.

Figure 5 - Gaussianity check of current fluctuations for a stress voltage of 0.5 V (open squares) and of 0.85 V (filled circles).

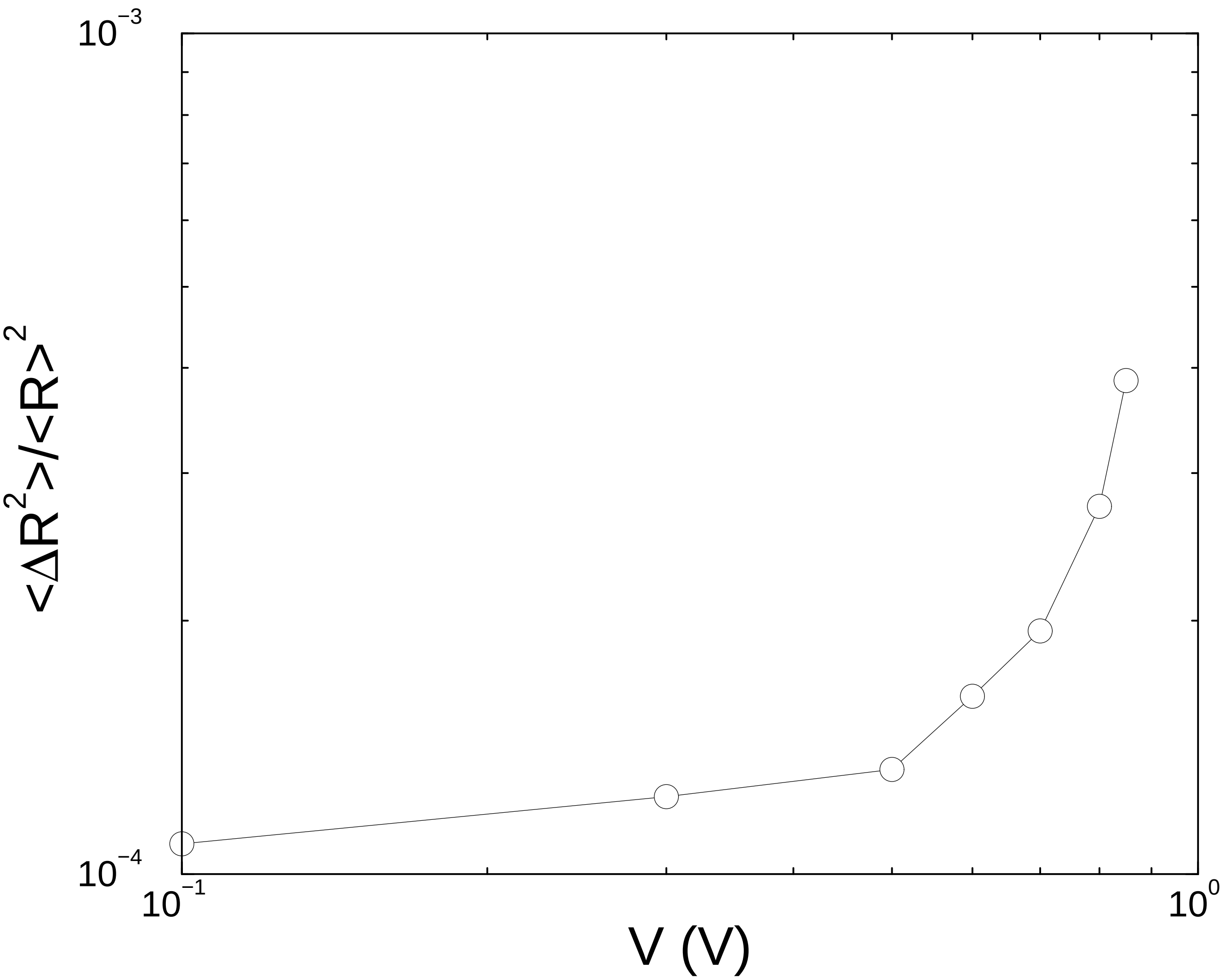


failure
Current (100nA)
Time (a.u)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1000
2000
3000
4000
5000

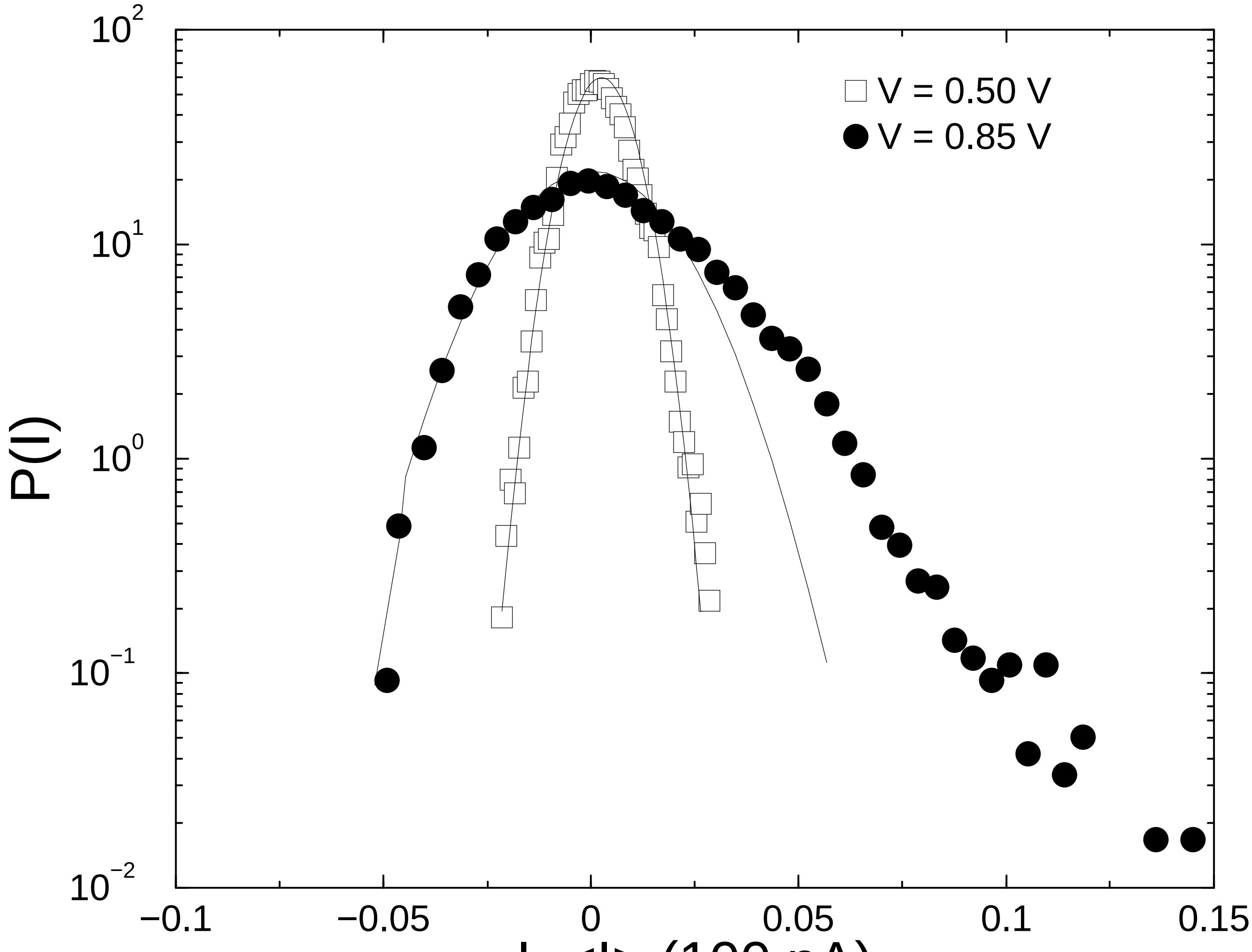

10
1
1
10
$V_b \sim R_{per}^{0.5}$
Breakdown voltage (V)
Perfect film resistance ($10^7\ \Omega$)



10^0
10^−2
10^−4
10^−6
10^−8
S_I(f) (a.u.)
1
10
100
f (a.u.)



10^{-3}
10^{-4}
10^{-1}
10^{0}
V (V)
$<\Delta R^2>/<R>^2$



10^2
10^1
10^0
10^{-1}
10^{-2}
P(I)
−0.1
−0.05
0
0.05
0.1
0.15
I−<I> (100 nA)
V = 0.50 V
V = 0.85 V